Testing Relativity by Lunar Laser Ranging*

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In 1969, a new era for studying relativity has started. With the first returns of laser pulses sent from observatories on Earth to reflector arrays on the Moon, a new space technique – Lunar Laser Ranging (LLR) – has been providing an ongoing time series of highly accurate Earth-Moon distance measurements.

LLR data analysis is carried out at the cm level of accuracy, for which all elements of the tracking process are modeled at appropriate (relativistic) approximation, i.e. the orbits of the major bodies of the solar system, the rotation of Earth and Moon, signal propagation, but also the involved reference and time systems as well as the time-variable positions of the observatories and reflectors, see [1] for more details.

We showed where relativity enters the LLR analysis and how the whole measurement process is modeled, including the major classical (Newtonian) effects like gravity field of Earth and Moon, tidal effects, ocean loading, lunar tidal acceleration (that causes the increase of the Earth-Moon distance by about 3.8 cm/year), etc.

By analyzing the 43-year record of range data, LLR is able to provide, among others, a dynamical realization of the International Celestial Reference System, parameters related to the selenocentric and terrestrial reference frames as well as (long-periodic) Earth Orientation Parameters.

Particularly, LLR is one of the best tools to test General Relativity in the solar system. It allows for constraining gravitational physics parameters related to the strong equivalence principle [2], geodetic precession, preferred-frame effects, or the time variability of the gravitational constant, [1], [3]. Recent results, especially, for the various relativistic parameters were presented, see Table 1.

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Table 1. IfE results for various relativistic parameters and estimated „realistic" errors.

Parameter	Results
Nordtvedt parameter η (test of the strong equivalence principle)	$(2.0\pm4.0) \times 10^{-4}$
Time variable gravitational constant $\dot{G}/G$ [yr^{-1}]	$(1.4\pm1.5) \times 10^{-13}$
$\ddot{G}/G$ [yr^{-2}]	$(4.0\pm5.0) \times 10^{-15}$
Geodetic precession [''/cy] (difference to predicted value of 1.92''/cy in general relativity)	$(-0.6\pm1.0) \times 10^{-2}$
Metric parameter $\gamma - 1$ (space curvature)	$(3.0\pm4.0) \times 10^{-3}$
Metric parameter $\beta - 1$ (non-linearity)	$(1.7\pm2.0) \times 10^{-3}$
$\beta - 1$ using $\eta = 4\beta - \gamma_{Cassini} - 3$ with $\gamma_{Cassini} - 1 = (2.1\pm2.3) \times 10^{-5}$	$(0.6\pm1.1) \times 10^{-4}$
Preferred-frame effect within special relativity $\zeta_1 - \zeta_0 - 1$	$(-0.5\pm1.2) \times 10^{-4}$
Preferred-frame effect α_1	$(3.0\pm3.0) \times 10^{-5}$
α_2 (coupled with the velocity of the solar system)	$(2.0\pm2.0) \times 10^{-5}$
Preferred-frame effect α_1 (coupled with the dynamics within the solar system)	$(1.6\pm3.0) \times 10^{-3}$
Influence of dark matter δ_{gc} [cm/s^2] (in direction to the galactic center, equivalence principle test)	$(0.0\pm2.0) \times 10^{-14}$

References

[1] Müller, J., L. Biskupek, F. Hofmann & E. Mai 2014: Lunar Laser Ranging and Relativity. Book chapter in "Frontiers in Relativistic Celestial Mechanics", Vol. 2 (ed. by. S. Kopeikin), de Gruyter, in press.

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[3] Müller, J., F. Hofmann, X. Fang & L. Biskupek 2014: Lunar Laser Ranging: recent results based on refined modelling. In: Earth on the Edge: Science for a Sustainable Planet (eds. C. Rizos & P. Willis). IAG Symposia Series, Springer, Vol. 139, p. 447–452.